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Simulated crop production under saline high water table conditions *

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Summary. Many irrigated lands in semi-arid regions of the world are underlain with saline high water tables. Water management is critical to maintain crop productivity under these conditions. A multi-seasonal, transient state model was used to simulate cotton and alfalfa production under various irrigation management regimes. The variables included in-season water application of 1.0 or 0.6 potential evapotranspiration (PET), and 18 or 33 cm pre-irrigation amounts for cotton. The water table was initially at a 1.5 m depth and a 9 dS/m salinity. A impermeable lower boundary at 2.5 m depth was imposed. Irrigation water salinity was 0.4 dS/m. Climatic conditions typical to the San Joaquin Valley of California were used for PET and precipitation values. The simulations were for no-lateral flow and also lateral flow whereby the water table was raised to its initial level prior to each irrigation event. Uniform application of 1.0 PET provided for relative cotton lint yields and alfalfa yields of 95% or more for at least 4 years. In-season irrigation of cotton with 0.6 PET had higher yields when associated with a 33 cm rather than an 18 cm pre-irrigation. Lateral flow provided for higher cotton lint yields production than the no-lateral flow case for each pre-irrigation treatment. The beneficial effects of lateral flow diminished with time because of the additional salt which accumulated and became detrimental to crop production. Substantial alfalfa yield reductions occurred after the first year when irrigation was set at 0.6 PET regardless of other conditions. Evaporation losses from the soil during the cotton fallow season were higher when the soil water content entering the fallow season were higher.

Many irrigated lands in semi-arid regions of the world are underlain with saline high water tables. These water tables pose a problem if they rise to the rootzone because the crop may be adversely affected by high salinity, anaerobic conditions and/or specific element toxicities. Lowering of the water table by placing subsurface drainage lines in the field is a common management practice. This approach has led to other problems in the San Joaquin Valley of California. Some drainage water has been placed in evaporation ponds. These ponds may contain high concentrations of trace elements such as Se, B, Mo, As, and U which have been implicated in the deformity of waterfowl. Evaporation ponds are also costly to the farmers as they displace productive cropping land.

An alternative to the use of drainage systems and evaporation ponds is the control of water table level with irrigation management. Application of more than crop evapotranspiration (ET) causes the water table to rise. Application of less than ET may cause the plants to use water from the water table and thus lower its elevation. When water from the water table is used by the crops, salts are brought into the rootzone. The consequences on crop yields depend on the crop salt tolerance and salinity of the water table.

Grimes et al. (1984) showed that substantial contributions to the seasonal cotton crop ET can come from a shallow saline groundwater and that the amount depends on the groundwater salinity. For a groundwater with a salinity of about 10 dS/m, a maximum contribution of about 30 percent occurred for a water table depth of about 1.5 m. Although this study found that a portion of the crop ET could be provided from the water table, the soil salinity increased due to the upward flow of saline groundwater. A pre-season irrigation is required to leach the accumulated salts and recharge the water table for long term productivity.

Non-uniform application of irrigation water resulting in variable application rates across the field is common. Non-uniform application of water could cause lateral flow beneath the water table. Water moves from points of excess irrigation where the water table is higher to points of deficit irrigation where the water table is lower. Lateral flow also causes movement of salt.

Water is a valuable commodity in the arid and semi-arid regions of the world. Water is lost by evaporation

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during the fallow season. Water can be saved if water loss during the fallow season is reduced. An understanding of the effects of irrigation management practices on fallow season evaporation is important to minimizing these losses.

Field research to determine the relationships between irrigation management on lands with a shallow saline water table is time consuming and expensive. Cardon (1990) described a computer simulation model for multiseason simulation of irrigation management. A greenhouse experiment was conducted with shallow saline water table for model verification. Results of multiseasonal simulation of cotton production under shallow saline water table conditions were reported by Cardon (1990).

The research reported in this paper extends the study of Cardon (1990). A different irrigation schedule on cotton was imposed to elucidate the effect of scheduling. The simulations were extended to a more salt sensitive alfalfa crop and the effects of lateral flow into the water table were investigated.

Table 1. Time and amount (cm) of irrigation water in cotton simulations

Pre-irrigation		
April 16	33 or 18	
In-season irrigations	1.0 PET	0.6 PET
June 16	11.7	7.02
July 15	19.8	11.9
August 15	23.4	14.0

Table 2. Parameter values of soil hydraulic properties used in the simulations

Name	Symbol	Value
Campbell parameters	b	3.26
	B	8.45
	ψ_e	−1.40 kPa
Hutson and Cass parameters	θ_i	0.42
	ψ_i	−2.23 kPa
	K_{sat}	0.89 cm/h
	θ_{sat}	0.48

Simulation procedures

A multi-seasonal transient state model was used to simulate crop production under various irrigation management regimes. This model, known as the modified van Genuchten-Hanks model (V-H model), calculates water flow in the vertical direction by the Darcy-Richards equation and plant response by the addition of a sink term (Cardon 1990). The van Genuchten portion of the model simulates plant response and the Hanks portion simulates infiltration and evaporation. The utility of the V-H model lies in its ability to predict relative yields as well as provide salt and water distributions in the profile at any desired time.

Cotton, a salt tolerant crop, and alfalfa, a less salt tolerant crop, were used in the simulations. The climatic conditions and irrigation practices were typical for the San Joaquin Valley of California. Scenarios for both crops included applications of water volumes equal to 1.0 or 0.6 potential evapotranspiration (PET) during in-season irrigation. The cotton crop received pre-irrigations of either 18 or 33 cm. The cotton growing season was April 16 to October 15 and received three in-season irrigations (Table 1). Cardon (1990) simulated five in-season irrigations. The seasonally variable PET and crop coefficient values were taken from Letey and Vaux (1985). Averages of these values were used for each transpiration period between irrigations.

Alfalfa was considered to be a perennial crop although essentially no production occurs during the winter months. The first irrigation was applied on March 1. Successive irrigations were applied on April 1 and May 1 and every two weeks thereafter until October 10. Each irrigation applied either 1.0 or 0.6 PET for the intervening period. The precipitation which occurs mostly in the winter months was equal to the long-term average between Mendota and Westside, California and the monthly average was applied in one event in the simulation. The crop coefficient for alfalfa was considered to be 1 throughout the year. The amount of irrigation on March 1 was equal to the PET between October 10 and March 1 minus the precipitation. The 0.6 PET treatment received an additional 30 cm on March 1 to recharge the profile.

The water table was initially at a depth of 1.5 m and a salinity of 9 dS/m. An impermeable layer at 2.5 m depth was used to simulate a worse case condition for the bottom boundary. The irrigation water salinity was 0.4 dS/m. The initial soil-water condition was 0.26 volumetric water content (matric potential of −0.01 MPa) which was incremently increased to 0.48 (saturation) at 1.5 m. The initial salinity level was equal to 0.4 dS/m in surface 1.4 m of soil and was incrementally increased to 9.0 dS/m at 1.5 m.

The osmotic and matric potentials which result in a 50% dry matter yield reduction must be specified. The osmotic potential chosen was −0.64 MPa for alfalfa (Maas 1986) and −0.96 MPa for cotton (Letey and Dinar 1986). The matric and osmotic potentials were assumed to have equal effects. The Hutson and Cass (1987) soil hydraulic property functions were used in the simulations. Values for parameters from the Campbell (1974) hydraulic property functions plus saturated hydraulic conductivity (K_{sat}) and saturated volumetric water content (θ_{sat}) must be specified. A summary of the hydraulic parameters used in the simulations is given in Table 2.

The V-H model is one-dimensional so that lateral flow cannot be directly included in the simulation. Lateral flow beneath the water table may have significant effects on the results. Lateral flows can be induced by non-uniform infiltration of water across the field. The model was manipulated to consider lateral flow of water and salt into the simulated area. This was done by reestablishing the water table at 1.5 m depth with 9 dS/m water before running the infiltration segment of the model for irrigation or precipitation. The amount of water and salt added to the profile by this procedure was dependent on the draw down of the water table by ET between irrigations.

Relative dry matter yields were calculated from the ratio of the computed evapotranspiration to the crop's potential evapotranspiration. For cotton, relative marketable lint yields were calculated using a regression equation relating cotton lint yield to dry matter yields (Davis 1983).

Results and discussion

The relative dry matter yield for cotton which received 0.6 PET are shown in Fig. 1. For convenience in reporting the simulated conditions are coded by three terms. The first is the amount of pre-irrigation, the second identifies whether lateral flow was simulated, and the third is the total annual irrigation amount. All scenarios had the same initial water and salt distribution and no pre-irrigation during the first year. Differences in yields for the first year are, therefore, due to the effects of lateral recharge of the water table. The 33 cm pre-irrigation maintained

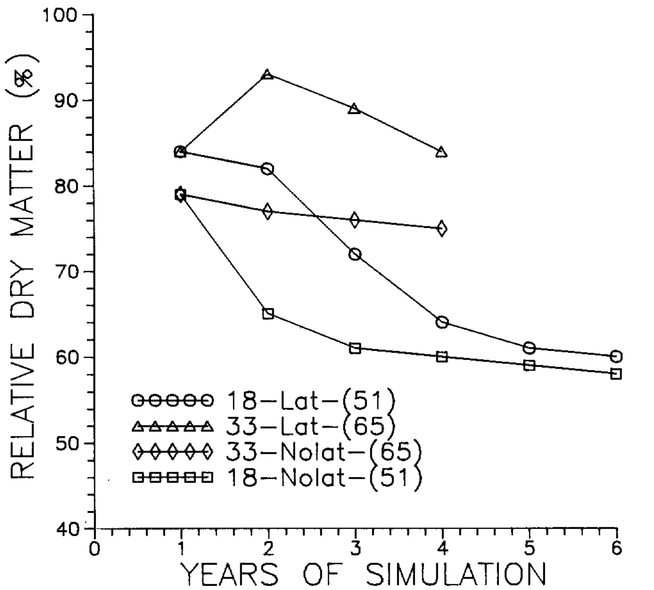

Fig. 1. Relative dry matter for cotton simulations that received 0.6 PET during the growing season. Encoded in the legend is the pre-irrigation amount (cm), the availability of water table recharge as lateral flow or no-lateral flow, and the total amount of water applied during the year (cm)

higher yields than the 18 cm pre-irrigation. For a given pre-irrigation the simulations which received lateral flow had higher yields than the no-lateral flow scenarios; however, this difference diminished with time. If lateral recharge of the water table occurs, more salt and water are brought into the soil. As salts accumulate, the benefits derived from additional water are diminished because of increased salt stress and the yields become reduced (Fig. 1).

The difference in the leaching capability of 18 cm-versus a 33 cm-pre-irrigation is depicted in Figs. 2 and 3. The soil solution salinity was standardized at a common saturated water content and expressed as the electrical conductivity of the solution (EC_{sat}). The larger pre-irrigation moved the salts deeper and provided more water so that yields were maintained at higher levels when compared to the lower pre-irrigation. The effect of lateral flow on salt accumulation is evident by comparing the salt distributions following the 33 cm-irrigation under lateral flow (Fig. 3) and no-lateral flow (Fig. 4). The salt concentrations are higher under the lateral flow condition, thus the benefits of additional water are offset by damage of additional salt.

Relative cotton lint yields for the 0.6 PET scenarios are shown in Fig. 5. Lint and dry matter yields follow the same trends except that lint yields are less affected by stress and are higher.

Relative dry matter yields for the 1.0 PET cotton scenarios are shown in Fig. 6. Relative dry matter yields higher than 90% were maintained for four years for all conditions. The computed relative cotton lint yields were all higher than 95% and are not illustrated. The lateral flow effects observed in the 0.6 PET scenarios (Fig. 1) are far less for the 1.0 PET scenario where only 18 cm-pre-irrigation case is slightly affected. The water table was not

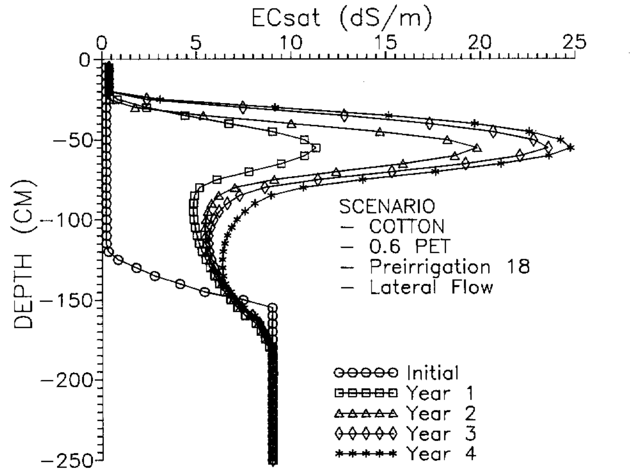

Fig. 2. The saturated electrical conductivity after a 18 cm pre-irrigation for the specified conditions

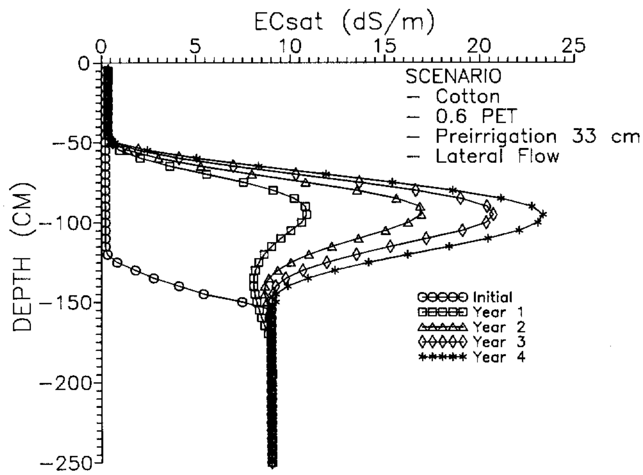

Fig. 3. The saturated electrical conductivity after a 33 cm pre-irrigation for the specified conditions

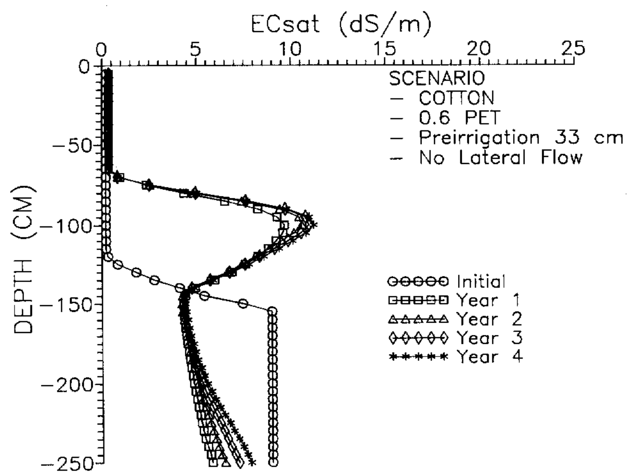

Fig. 4. The saturated electrical conductivity after a 33 cm pre-irrigation for the specified conditions

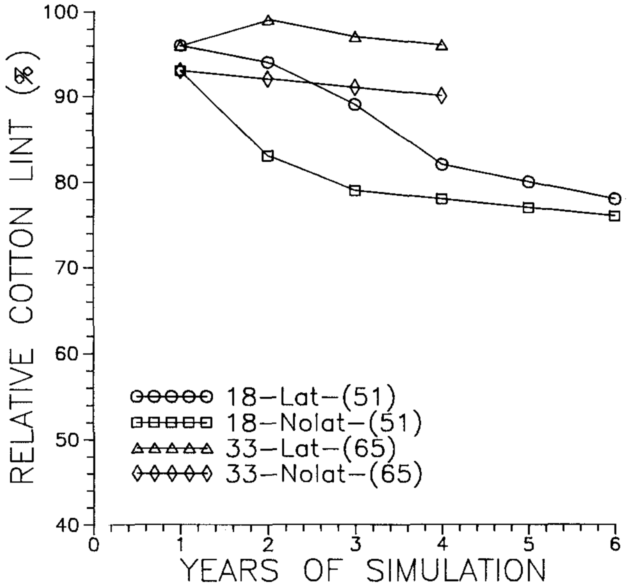

Fig. 5. Relative cotton lint from the simulations which received 0.6 PET during the growing season. The legend is encoded as Fig. 1

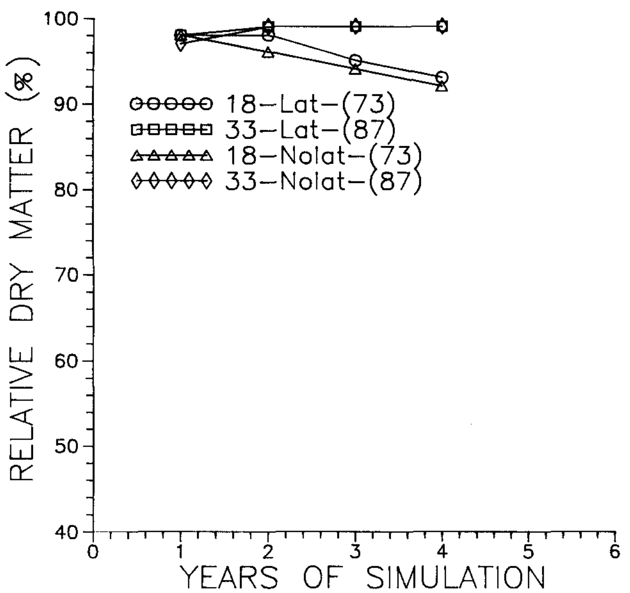

Fig. 6. Relative dry matter for the cotton simulations which received 1.0 PET during the growing season. The legend is encoded as Fig. 1

drawn down extensively under 1.0 PET irrigation so that very little water and salt was added by the lateral flow. The 18 cm-pre-irrigation without lateral flow was not adequate to fully recharge the profile so a slight downward trend in yields with time was computed.

The relative dry matter yields for alfalfa are shown in Fig. 7. The 1.0 PET irrigations maintained relative yields higher than 95% for four years. When 1.0 PET is applied, little water is taken up from the water table and therefore little salt accumulation occurs. The cases which received 0.6 PET had the lowest yields that dropped sharply in the second year. The 0.6 PET plus a 33 cm irrigation had a

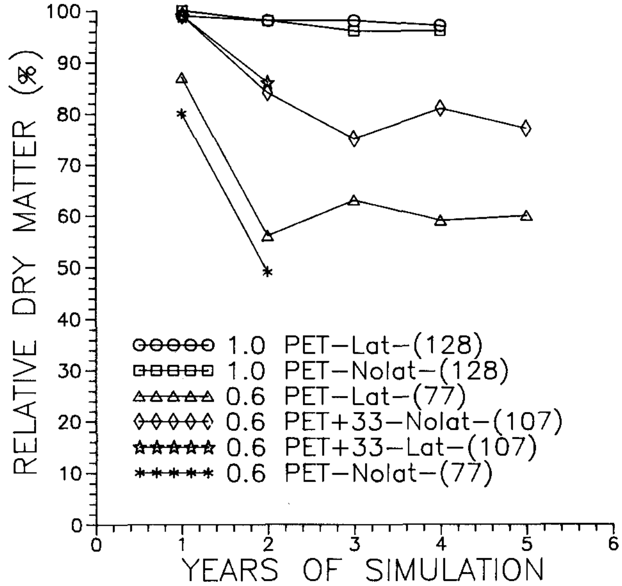

Fig. 7. Relative dry matter for the alfalfa simulations. Encoded in the legend is the fraction of PET applied during irrigation, the +33 incidates an additional irrigation of 33 cm, lateral no-lateral flow, and the total amount of water applied during the year (cm)

high reduction in yield in the second year but tended to stabilize at about 80% thereafter. Irrigation of 0.6 PET plus lateral flow had yields which stabilized at about 60%. The water from the soil and water table was largely extracted from the 0.6 PET irrigation without lateral flow after the second season so no additional simulations were conducted. The soil profile with 0.6 PET irrigation and lateral flow could not accommodate the 33 cm spring irrigation without saturation and runoff after the second year so that case was not simulated beyond the second year.

Two of the 0.6 PET cases exhibited slight oscillation in the relative yield from year to year (Fig. 7). These oscillations occur because when yields are higher, more water is extracted and more salts move into the rooting zone. The following year the yields are reduced because of less water and higher salinity. These lower yields result in lower water extraction so that subsequent irrigations cause additional leaching. The third crop then starts off with less salts in the profile and grows better than the second year's crop. This cycle is dampened with time.

The lateral flow component to the simulations was designed to gain insight to the effects of non-uniform irrigation on crop production under saline high water table conditions. Lateral flow within the water table was assumed to occur from areas receiving larger to areas receiving lower quantities of irrigation water. The crop production model is one-dimensional and does not accommodate lateral flow. Our analyses only considered the effects of lateral flow into the areas of deficit irrigation and this was done by imposing the condition that the water table was restored to its original level with saline water before each irrigation. The simulations only consider one aspect of non-uniform irrigations so full consequences of irrigation uniformity cannot be drawn from the results. Nevertheless, lateral flow caused higher yields than no-lateral flow (Figs. 1 and 7) so that to the extent that lateral flow is enhanced by the presence of the water table, the negative effects of non-uniform irrigation are diminished. This benefit was not maintained for many seasons because the lateral transfer of salt caused an accumulation that decreased yield. Under the simulation condition, lateral flow never caused lower yields than the no-lateral flow condition except for alfalfa which was flooded from a large 33 cm irrigation in addition to the lateral flow. When yields became depressed from salt accumulation, the ET decreased so that very little if any water was extracted from the water table. If the water table was not lowered, no additional water and salt was added to raise the water table prior to irrigation. In effect, lateral flow did not occur even though the opportunity for flow existed in the simulation. In reality, if the same amount of water was applied to the field each year, and yields in the deficit irrigated areas of the field decreased each year (Fig. 1), the average water table would rise because the average ET for the field decreased each year. This condition would allow continued lateral flow of water and salts so that the deficit irrigated parts of the field would become more severely impacted than depicted by the present analyses. Thus, the presence of a high water table may partially mitigate the negative consequences of non-uniform irrigation in the short term and would either have no effect or enhance the negative consequences in the long run if the water table is saline.

The consequences of lateral flow away from areas receiving higher amounts of water were not determined. However, the results can be inferred. Assuming that the average water application to the field is equal to ET, the areas receiving the highest amount of water would have water in excess of ET. Lateral movement away from an area would remove water and salts. Irrigation with water equal to replace ET losses resulted in almost maximum yields of both cotton (Fig. 6) and alfalfa (Fig. 7). So maximum yields would be expected in the areas receiving highest water application if the "excess" had the opportunity to flow laterally to "deficient" areas. Removal of salts would enhance this condition.

Conclusions

The results of these simulations indicate that near maximum yields of cotton and alfalfa can be maintained for several years in the presence of a saline high water table if a non-saline irrigation water is available and proper irrigation management is imposed. Uniform irrigation whereby the water lost by ET is quantitatively replaced by irrigation allows the maximum yield to be achieved. Non-uniform irrigation results in some areas receiving deficit irrigation. The effects of deficit irrigation may be partially mitigated for a short time by lateral flow. However, the lateral transfer of salts and their subsequent accumulation in the deficit irrigated areas would result in significant reduction in yields in these areas. Irrigation uniformity is therefore a critical factor in the long term crop yield potential under saline high water table conditions.

Table 3. Evaporation (cm) during the fallow season of cotton for various scenarios

Irrigation	Pre-irrigation cm	Lateral flow	Applied water cm	Evaporation (cm) Year 1	2	3	4
1.0 PET	33	yes	87	18.1	22.7	23.4	23.6
0.6 PET	33	yes	65	15.7	17.4	18.6	19.5
1.0 PET	33	no	87	15.2	17.1	19.3	20.7
0.6 PET	33	no	65	12.2	12.0	12.0	12.0
1.0 PET	18	yes	73	18.1	19.0	19.5	20.1
0.6 PET	18	yes	51	15.7	17.6	19.0	20.3
1.0 PET	18	no	73	15.5	14.5	13.8	13.4
0.6 PET	18	no	51	12.3	11.3	10.9	10.6

Evaporation amounts during the fallow season of cotton are summarized in Table 3. The scenarios which provided the most water (including lateral flow) had the highest evaporation amounts. An exception is observed with the irrigation at 0.6 PET receiving lateral flow where the evaporation was slightly higher under the 18 than the 33 cm pre-irrigation. This can be explained by examining the relative yields for these two cases in Fig. 1. The 33 cm pre-irrigation simulation had much higher yields and therefore transpired more water than the 18 cm simulation. In 33 cm simulation actually went into the fallow season with a drier profile and therefore evaporated less. Evaporation during the fallow season is dependent upon moisture content at the end of the growing season. Soil evaporation is less than potential evaporation when the soil surface becomes dry, a condition which will be more prevalent when the soil profile contains less water. The potential evaporation for the condition simulated was 31.4 cm. In every case, the evaporation was less than the potential evaporation (Table 2). Allowing the crop to extract as much water as possible without yield reduction before entering the fallow season is desirable for water conservation. Delay of irrigation to recharge the profiles until just before the crop season is a water conservation practice.

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